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Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements

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Abstract

Regulated deficit irrigation (RDI) has been proposed as one of the most promising irrigation strategies for hedgerow fruit orchards with high plant densities. Scheduling a RDI strategy, however, is highly demanding, since the targeted water savings must be achieved at the same time that episodes of excessive water stress are avoided when the crop is most sensitive to drought. Here we tested an approach to schedule a RDI strategy supplying 45% of the crop irrigation needs, specially designed for hedgerow olive orchards. Our approach is based on the use of a water stress indicator derived from the shape of the daily curves recorded with ZIM sensors, which are related to the leaf turgor pressure. We worked in a mature, fully productive 'Arbequina' olive orchard with 1667 trees ha^{-1}, under both a daily irrigated (FI) treatment and the mentioned RDI strategy. We found that the relation between the shape of the curves and the tree water stress levels holds for olive trees of different age under a wide range of growing conditions. We were able to schedule irrigation just from the visual analysis of the curves derived from the ZIM outputs, without any further data processing. A comparison with the crop coefficient approach showed that, with our approach, we achieved greater water savings without affecting neither the trees water status nor the crop performance. Still, further studies are required to confirm whether empirical aspects of our approach are limiting and, if so, to derive suitable alternatives.

1. Introduction

In most olive orchards irrigation is required to achieve an acceptable profitability (Gucci et al., 2012). When the purpose of supplying water is not only to increase yield, but also to raise water productivity, to control vigour and to improve fruit and oil quality, irrigation scheduling becomes a challenge. In addition to a deep knowledge of the crop physiology related to water use, precise irrigation requires effective tools for monitoring water stress. Our understanding of both the olive adaptation to water stress and its response to irrigation has improved substantially in the last decades, as summarized in reviews such as those by Connor and Fereres (2005), Sanzani et al. (2012) and Fernández (2014a). In parallel, advances on electronics and data transmission have allowed a development of systems for the automatic and continuous monitoring of water stress in fruit tree orchards, including olive (Zimmermann et al., 2008; Fernández et al., 2008; Ortuño et al., 2010). Combined with remote imagery of the whole orchard (Zarco-Tejada et al., 2009; Gonzalez-Dugo et al., 2013), some of these systems have proven to possess a high potential for scheduling irrigation in commercial orchards (Fernández 2014b).

Olive orchards with plant densities over 1500 trees ha^{-1}, also called super-high-density (SHD) olive orchards (Vossen et al., 2004), are especially sensitive to irrigation supplies. If those are too low, not only crop performance but also the productive life of the orchard can be reduced. If irrigation supplies are too high, tree vigour can be excessive, making mechanical harvesting difficult (León et al., 2007) and decreasing the long-term crop performance from heterogeneous light distribution around the canopy (Connor et al., 2009; Gómez-del-Campo et al., 2009). In addition, both fruit and oil quality are affected by irrigation management (Morales-Sillero et al., 2008; Gomez-Rico et al., 2009; García et al., 2013). Current knowledge shows that a regulated deficit irrigation (RDI) strategy together with an effective system to monitor the tree water stress could be the best approach for an effective irrigation management in SHD olive orchards (Gómez-del-Campo, 2013; Fernández et al., 2013).

The suitability of different irrigation strategies for olive orchards, including RDI, has been addressed by various authors (Grattan et al., 2006; Pastor et al., 2007; Proietti et al., 2012; Fernández et al., 2013). For the monitoring of water stress, recent efforts have focused mainly on plant-based sensors with data transmission systems that allow automatic and continuous recording of main physiological variables related to the tree water status. This is the case for sap flow (Fernández et al., 2008; Ramos and Santos, 2009; Rousseaux et al., 2009), trunk diameter (Pérez-López et al., 2008; Moriana et al., 2010; Cuevas et al., 2010) and leaf turgor (Zimmermann et al., 2008; Ache et al., 2010; Fernández et al., 2011). Details on the required characteristics of any plant-based sensor to schedule irrigation are given in Fernández and Cuevas (2010). Recently, Fernández (2014b) assessed the applicability of systems based on sap flow, trunk diameter and leaf turgor related measurements to monitor water stress and to schedule irrigation in commercial orchards. They concluded that the success of any of these methods relies, among other things, on the possibility of deriving a user-friendly water stress index from the collected records.

In the assessment by Fernández (2014b), the ZIM system (YARA ZIM Plant Technology, Hennigsdorf, Germany), which provides information on the leaf turgor pressure (P_c), was considered as one of the most promising systems to schedule irrigation in commercial olive orchards. In addition to being sensitive and reliable, as well as robust enough for working under field conditions for long periods, the ZIM system provides a user friendly water stress index, suitable for deriving irrigation decisions just from the visual analysis of the raw outputs. The potential of the index to schedule irrigation in a SHD olive orchard was first tested by Fernández et al. (2011). Basically, the ZIM system uses the leaf patch clamp pressure probe, or ZIM probe (Zimmermann et al., 2008), together with transmission data systems for the user to access to the collected information through any computer, tablet or smartphone connected to the Internet.

The ZIM probe measures the leaf patch output pressure (P_p), which is inversely coupled with P_c. For trees with abundant water supply, daily P_p curves show maximum values during the day, when P_c decreases because of transpiration, and minimum values at night, during leaf rehydration after stomatal closure. For trees under water stress conditions, however, the shape of the curve changes. Fernández et al. (2011) observed, in 'Arbequina' olive trees, half-inversed and completely inversed diurnal P_p curves when values of midday stem water potential (Ψ_{stem}) dropped below *ca*. −1.7 MPa. The shape of the curves became back to normal a few days after rewatering, the number depending on the level of water stress previously reached. Fernández et al. (2011) made concomitant measurements of P_p and leaf and stem water potential (Ψ_{stem}) recorded with a Scholander-type pressure chamber, and mentioned three States, 1 to 3, according to the shape of the diurnal P_p curve recorded in olive trees under increasing water stress. In a joint work between the research groups of Zimmermann and Fernández, the three States were further defined for olive (Ehrenberger et al., 2012). In State 1 (low stress) the P_p curve showed maximum values during the day and minimum values at night. This was typical of leaves close to maximum turgor (P_c >> 50 kPa), in trees with $\Psi_{stem} > -1.2$ MPa. In State 2 (moderate water stress, $P_c \approx 50$ kPa, $-1.2 \text{ MPa} > \Psi_{stem} > -1.7$ MPa) P_p values started to increase from early morning, decreased for some time on the central hours of the day and recovered in the afternoon. In State 3 (severe water stress, P_c << 50 kPa, $\Psi_{stem} < -1.7$ MPa) the P_p curve was fully inversed, with minimum values during the day and maximum values at night. The work of Fernández et al. (2011) refers, however, to a single year, and measurements were made on young trees (4 years old) only. That by Ehrenberger et al. (2012) was also made with young olive plants, in this case potted plants. Our first hypothesis is that the relation between the State shown by P_p curves and the ranges of tree water stress established according to Ψ_{stem} values also holds for mature, fully productive olive trees. Taking into account that the water stress levels at which the P_p curve changes from State 1 to Sate 2 (-1.2 MPa) and from State 2 to State 3 (-1.7 MPa) are close to reference threshold levels of water stress in olive (Moriana et al., 2010; 2012), and that the change in State is a visual indicator, easy to use by farmers without specific training, our second hypothesis is that such indicator can be used to schedule regulated deficit irrigation in commercial SHD olive orchards.

The aims of this work were (i) to prove whether the correspondence between States 1, 2 and 3 of the P_p curves and the Ψ_{stem} threshold levels reported by Fernández et al. (2011) and Ehrenberger et al. (2012) holds for mature, fully productive olive trees, and (ii) to evaluate the suitability of an irrigation scheduling approach based on changes among States 1 and 3 to schedule regulated deficit irrigation in a super-high-density olive orchard.

2. Materials and methods

2.1. Orchard characteristics and irrigation management

The experiments were made in 2013 and 2014, in the same super-high-density olive (*Olea europaea* L., cv Arbequina) orchard where Fernández et al. (2011, 2013) made their experiments. The orchard, located at 25 km to the east of Seville (37° 15′ N, −5° 48′ W), had trees at the top of 0.4 m high ridges, planted at 4 m × 1.5 m (1,667 trees ha^{-1}), with tree rows oriented N-NE to S-SW. Climate in the area is Mediterranean with mild, wet winters and hot, dry summers. The rainy period is between September and May, being dry for the rest of the year. Average values of precipitation (*P*) and potential evapotranspiration (ET_o) in the area are 540 mm and 1,528 mm, respectively (period 2002-2014). In the hottest months, July and August, maximum values of air temperature were over 40 °C and rarely over 45 °C. In the coldest months, December and January, minimum values of air temperature were seldom below 0 °C and very rarely below −5 °C. Additional details on the trees, environmental characteristics and orchard management are given by Fernández et al. (2011, 2013).

In 2013, when the trees were 7 years old, we had a full irrigation (FI) treatment in which trees were daily irrigated for the whole irrigation season to replace 100% of the irrigation needs (IN), and a regulated deficit irrigation treatment (45RDI) for which the total water supplied along the season was aimed to replace 45% of IN. The irrigation strategy for this 45RDI treatment is shown in Fig. 1. Basically, the irrigation amounts (IA) must be equal or close to IN in three periods of the year when the crop is most sensitive to water stress (Fernández 2014a). For the rest of the year just one or two irrigation events per week are applied. In our area, period 1 (around bloom) falls into the rainy season, so irrigation is usually required in periods 2 and 3 only. In 2013 we used the crop coefficient approach (Allen et al., 1998) to schedule irrigation. This is why we named $45RDI_{cc}$ the 45RDI treatment applied this year. Every Monday of the irrigation season the irrigation needs were calculated as IN = $ET_c - P_e$, being ET_c the crop evapotranspiration estimated by the crop coefficient approach and P_e the effective precipitation, assumed to be 75% of the precipitation recorded by the weather station in the orchard. The calculated IN values were applied daily to the FI trees. For the $45RDI_{CC}$ trees irrigation was reduced according to Fig. 1. Thus, the $45RDI_{CC}$ trees were irrigated daily in periods 2 and 3, but for the rest of the irrigation season water was supplied just once or twice per week. The crop coefficient (K_c) values were adjusted for the orchard conditions from measurements made from 2010 to 2012 by Fernández et al. (2013). The resulting K_c values were 0.60 in May, 0.63 in June, 0.57 in July and August, 0.65 in September and 0.69 in October. The calculated irrigation doses were input in an irrigation controller (Agronic 2000, Sistemes Electrònics PROGRÉS, S.A., Lleida, Spain) and water was applied through a pipe per tree row with three 2 L hour^{-1} drippers per tree, 0.5 m apart. Fertilizers were injected into the irrigation system once a week during the whole irrigation season, to match the tree requirements (Fernández et al., 2013). All treatments received the same amounts of fertilizers. We used a randomized block design with four 12 m × 6 m plots per treatment. Each plot contained 24 trees, and measurements were made in the central 8 trees.

In 2014 we had the FI and the $45RDI_{CC}$ treatments, both scheduled with the crop coefficient approach. In addition, we had a $45RDI_{TP}$ treatment, for which we also used the 45RDI strategy depicted in Fig. 1 but scheduled from outputs of the ZIM system. As detailed in Section 2.2, we instrumented with ZIM probes one tree per plot, in three plots out of the four $45RDI_{TP}$ plots. At the beginning of both period 2 and period 3, all RDI trees showed moderate to severe levels of water stress, because of the lack of water in the soil caused by the reduced irrigation applied on the weeks before. We then supplied daily IA values amounting to 120% IN on the first three days of both period 2 and 3. This was enough for the daily P_p curves recorded in those trees to change from State 2 or 3 to State 1. For the rest of the period, every morning we visualized the three P_p curves recorded the day before, one from each of the three trees instrumented with ZIM sensors, and adjusted irrigation to the $45RDI_{TP}$ trees according to the State of the P_p curves and the 3-day weather forecast given through Internet. Thus, when one out of the three P_p curves changes from State 1 to State 2 and the weather forecast announced increasing atmospheric demand, the IA value for the $45RDI_{TP}$ treatment was increased by 15%. If atmospheric demand was expected to decrease, or the most sensitive instrumented $45RDI_{TP}$ tree did not show a change from State 2 to State 3, IA was not modified. In case of a change from State 2 to State 3, or a second tree changing from State 1 to State 2, IA was increased by 15%. When the State shown by the P_p curves indicated a recovery of the tree water status, IA was decreased, again by 15%. Outside of periods 2 and 3, when irrigation is applied just once or twice per week, IA values were applied according to Fig. 1. In our case, and because we were using the crop coefficient approach to schedule irrigation both in the FI and $45RDI_{CC}$ treatments, we used the calculated IN values to derived the IA values for the $45RDI_{TP}$ trees on the weeks before, in between, and after periods 2 and 3.

2.2. Soil, plant and weather measurements

Soil water status was monitored as detailed in Fernández et al. (2013). Basically, a Profile probe (Delta-T Devices Ltd, Cambridge, UK) was used to record volumetric soil water content (Θ_v) values in the root zones of three trees per treatment, and the values used to calculate changes on the relative extractable water (REW) along the two irrigation seasons, for all treatments. Previous work in the orchard showed that records in three trees per treatment were enough to derive reliable REW values (Fernández et al., 2011, 2013).

Both in the FI and 45RDI treatments, and before the beginning of the 2013 and 2014 irrigation seasons, one central tree per plot was instrumented, in three of the four plots, with ZIM probes (YARA ZIM Plant Technology, Hennigsdorf, Germany). The instrumented trees were representative of those in the treatment, in terms of size, leaf area, water status and gas exchange. As for the REW values, records from three trees per treatment were enough to monitor the tree water status variability within each treatment, according to the findings by Fernández et al. (2011). In each instrumented tree, a ZIM probe was clamped on a leaf of the east side of the canopy, at *ca*. 1.5 m above ground. Once every 5 min the output of the probe was sent via radio to a datalogger with a GPRS modem for data transfer to a server own by ZIM Plant Technology GmbH, to which we accessed via Internet. The ZIM probes were left working until the end of the irrigation seasons.

Measurements of both predawn (Ψ_{pd}) and midday stem water potential (Ψ_{stem}) were made with a Scholander-type pressure chamber (PMS Instrument Company, Albany, Oregon, USA). Once every other week during the entire irrigation seasons, one leaf per tree from two representative trees per plot (n = 8) were sampled. For Ψ_{stem} we selected leaves close to a main branch and wrap them in aluminium foil ca. 2 h before measurements. These leaves were sampled from 11.30 GMT to 12.30 GMT. Both for Ψ_{pd} and Ψ_{stem}, the sampled leaves were put into an aluminium canister with wet filter paper inside and taken to the pressure chamber within a maximum of 3 min after sampling. Sampled leaves were taken from trees next to those instrumented with ZIM probes, such that leaf sampling did not affect P_p outputs.

Main weather conditions in the orchard were recorded every 30 min with a Campbell weather station (Campbell Scientific Ltd., Shepshed, UK). In addition, weather records required to calculate ET_o for the crop coefficient approach were collected from a standard weather station of public access through the Internet, belonging to the local government (Fernández et al., 2013).

Harvesting was made on October 29th 2013, day of year (DOY) 302 and on November 21st 2014 (DOY 325). The trees were manually harvested and total fruits per plot were weighted separately. From the recorded fruit yields and the total IA per treatment we calculated the irrigation water productivity (WP) as the amount of marketable product per hectare and unit of supplied water.

2.3. Statistical analysis

Data shown are mean ± standard error. For the statistical analysis we used linear mixed models (LMM) with Tukey's all-pair comparisons to analyse the differences between irrigation treatments (fixed factor) statistically significant at $p < 0.05$. These analyses were performed by R software (R Core Team, 2012) with R packages 'nlme R' (Pinheiro et al., 2011) and 'multcomp R' (Hothorn et al., 2008).

3. Results

Total IA applied in 2013 to the FI treatment was lower than expected because of malfunctioning of the irrigation pump at the beginning of the irrigation season. This explains the lack of irrigation until June 18th, DOY 169 (Fig. 2A) and the decrease on REW values on those days (Fig. 2C). For the rest of the 2013 irrigation season, and also for the 2014 irrigation season, IA ≈ IN in the FI treatment and REW values were close to 1, suggesting non-limiting soil water conditions (Figs. 2C,D). In the 45RDI treatments, however, the REW dynamics agreed with changes on IA established by the applied RDI strategy. Thus, in periods 2 (June) and 3 (late August – mid September), REW values of *ca.* 0.8, were recorded, while in between periods 2 and 3 (July-August) and after period 3 (from mid September), REW values were lower, due to the low IA applied on those weeks to the 45RDI trees. Data of 2014 shows that in period 2 (DOY 154-185), IA values amounted to 72.2 mm in $45RDI_{CC}$ and to 61.5 mm in $45RDI_{TP}$. In period 3 (DOY 238-259) these values were 66.8 mm in $45RDI_{CC}$ and 67.1 mm in $45RDI_{TP}$. For the FI treatment, IA values were 93.1 mm in period 2 and 69.7 mm in period 3. Differences in IA between treatments had little impact on REW values in those two periods (Fig. 2D). Consequently, similar water stress levels were found in trees of all treatments, for both period 2 and 3, as Ψ_{pd} (Figs.

3A,C) and Ψ_{stem} (Figs. 3B,D) values show. In between those periods the trees' water stress increased considerably in the 45RDI treatments, as expected. After period 3 the autumn rainfall (Figs. 2A,B) contributed to keeping low values of water stress (Fig. 3).

Since our irrigation scheduling approach was based on outputs of the ZIM probe, we wanted to compare those outputs with measurements with the Scholander-type pressure chamber, a widely used instrument to monitor olive water stress (Moriana et al., 2012; Naor et al., 2013). In Fig. 4 we show data from both methods, collected in May and September, i.e. before and after the highly demanding mid-summer period. The shown P_p curves correspond to a $45RD_{CC}$ tree (Fig. 4A) and a FI tree (Fig. 4B). All the other instrumented trees showed a similar behaviour. Values of Ψ_{pd} and Ψ_{stem} showed that trees of both treatments had similar water stress levels in May and in September. Values of P_p, however, were greater in September than in May, for both the $45RDI_{CC}$ and the FI trees. Results in Fig. 4, therefore, suggest that water stress monitoring should not rely on absolute P_p values, at least for our orchard conditions.

Our irrigation scheduling approach, however, relies on the State shown by the P_p curves, and not on absolute values. As mentioned in the Introduction, Fernández et al. (2011) and Ehrenberger et al. (2012) found that State 1 was observed in olive trees with $\Psi_{stem} > -1.2$ MPa, Sate 2 in trees with -1.2 MPa $< \Psi_{stem} < -1.7$ MPa and State 3 in trees with $\Psi_{stem} < -1.7$ MPa. But they both worked with young trees only. To test the suitability of our irrigation scheduling approach for olive trees of any age, from young to fully mature, highly productive trees, we made Fig. 5. In this figure Ψ_{stem} values measured in trees of all treatments are plotted against the State shown by the P_p curves collected on the same days. The figure shows the data we collected in 2013 and 2014, and also data collected by our team from 2010 in the same orchard, when we began this set of studies on scheduling regulated deficit irrigation in super-high-density olive orchards. Including data from our previous work allows for a more robust assessment on the relation between Ψ_{stem} values and the State shown by P_p curves. Measurement details for the 2010-2013 period can be seen in Fernández et al. (2011, 2013) and Diaz-Espejo et al. (2012). Figure 5 shows data collected in 4 to 8-year-old trees, under a wide range of both soil water conditions and atmospheric demand. In the 68.3% of the cases in which P_p curves were in State 1 we found Ψ_{stem} values to be > -1.2 MPa, and in the 81.8% of the cases in which P_p curves were in State 3, $\Psi_{stem} < -1.7$ MPa. Thus, both for States 1 and 3 we got similar results, in most cases, than those reported by Fernández et al. (2011) and Ehrenberger et al. (2012). However, about one third only of the trees in which P_p records showed State 2 had Ψ_{stem} values in between -1.2 and -1.7 MPa, as previously reported by those authors. This lack of agreement can be explained, at least in part, by State 2 being not always easy to identify. Both States 1 and 3 can be clearly identified from the shape of the P_p curves. However, at moderate levels of water stress typical of State 2, decreases in the P_p values collected at the central hours of the day were highly variable, being not always easy to identify whether the shape of the P_p curve suggested State 2 or it was just noise caused by changing atmospheric conditions.

Changes among States observed in 2014 in each of the trees instruments with ZIM probes, as well as the average Ψ_{stem} values for each treatment, are shown in Fig. 6. This figure illustrates, in fact, the tree-to-tree variability of the State shown by the P_p curves collected in our orchard. Trees of the FI treatment always showed State 1, except for days of sudden increase in ET_o, such as DOY 242-244. The 45RDI$_{TP}$ trees showed State 1 for most days of periods 2 and 3. An exception was at the beginning of period 3, when the available water in the soil was very low after the mid-summer period of reduced irrigation. State 2 was also observed on some days of Period 2, likely because of the reduced IA, which amounted to 0.68% of IN only (Fig. 7). In between periods 2 and 3, all 45RDI$_{TP}$ trees showed State 2 or 3, as expected. In the autumn irrigation was also reduced, but the total water supplied by irrigation and precipitation (Fig. 2B) was enough to avoid severe water stress, as commented when reporting findings shown in Fig. 3. The 45RDI$_{CC}$ trees showed a similar behaviour than the 45RDI$_{TP}$ trees, with the difference of a lower recovery from water stress after the beginning of both periods 2 and 3. This can be explained by the fact that 45RDI$_{TP}$ trees were irrigated with IA = 120% IN on the first three days of each period, as explained in Section 2.1.

Figure 7 shows the results from applying our irrigation approach to schedule the 45RDI$_{TP}$ treatment. Figures 7A and 7C show the P_p curves collected in a 45RDI$_{TP}$ tree, for periods 2 and 3, respectively. We chose the tree in which State 2 appeared earlier. The other two trees showed similar behaviour, although signs of water stress appear one or two days later than in the tree used for Fig. 7. A certain tree-to-tree variability in fruit tree orchards can be expected, due to spatio-temporal variations of soil and plant conditions (Fernández and Cuevas, 2010). Arrows in Fig. 7 show the days on which we increased or decreased irrigation according to the State shown by the P_p curve. Figures 7B (period 2) and 7D (period 3) show differences in the daily IA values when estimated with the crop coefficient approach (45RDI$_{CC}$) as compared to our irrigation scheduling approach based on the ZIM system (45RDI$_{TP}$). Also shown are the total IA applied for both treatments in each period, expressed as a percentage of the IN calculated for the period. These data show that in period 2 the amount of water supplied by irrigation was lower in 45RDI$_{TP}$ than in 45RDI$_{CC}$ (Fig. 7B). In period 3, when irrigation demands were lower, IA values in 45RDI$_{TP}$ and in 45RDI$_{CC}$ were similar (Fig. 7D).

The crop response to the irrigation treatments in terms of fruit yield and irrigation water productivity (WP) is shown in Table 2. The trees were already fully productive in 2013 and 2014, as expected for their age (7 and 8 years old, respectively). Considering data of both years, and averaging results from the 45RDI$_{CC}$ and 45RDI$_{TP}$ treatments, the 45RDI trees, which received 53.9% of the total IA supplied to the FI trees (Table 1), had a fruit yield of 72.4% of that in FI (Table 2). Values of WP increased with RDI in 30.2%, on average. For 2013, however, WP data are not reliable, because of the problem with the irrigation pump we had at the beginning of the 2013 irrigation season (Section 3). Data from 2014 show that differences in fruit yield between $45RDI_{TP}$ and $45RDI_{CC}$ were not significant (p = 0.54 and p = 0.22, respectively). Still, data of one year only is not enough to evaluate the impact of the irrigation treatment on production.

4. Discussion

As mentioned above, our group began in 2010 a set of studies to identify both a suitable RDI strategy for hedgerow olive orchards with high tree densities (SHD olive orchards) and a reliable, user-friendly water stress indicator to schedule irrigation. In a first set of experiments made from 2010 to 2102, Fernández et al. (2013) evaluated the impact on crop performance of an earlier version of the RDI strategy, with two irrigation levels (30% and 60% of IN). Experiments were run in parallel to assess the performance of different water stress indicators, from the conventional leaf and stem water potential, and stomatal conductance, to new plant-based methods for automatic and continuous monitoring of water stress. These experiments with concomitant measurements of a wide range of variables related to the water status in the soil, plant and surrounding atmosphere, provided insight into the links between physiological processes in olive trees under water stress and outputs from sap flow, trunk diameter variations and leaf turgor related measurements (Fernández et al., 2011; Diaz-Espejo et al., 2012; Rodriguez-Dominguez et al., 2012; Cuevas et al., 2013). Those findings, together with contributions from other authors on the usefulness of those plant-based sensors to monitor water stress in fruit trees, allowed for detailed assessments on the potential of each method for monitoring water stress and schedule irrigation. The work by Fernández et al. (2008), Ramos and Santos (2009) and Rousseaux et al. (2009) show, to a good extent, the advantages and disadvantages of sap flow measurements to improve water management in olive and other fruit trees. The same can be said for trunk diameter variations on the work by Pérez-López et al. (2008), Moriana et al. (2010) and Cuevas et al. (2010). And the potential of using leaf turgor related measurements with that purpose was evaluated by Ben-Gal et al. (2010), Rüger et al. (2010) and Zimmermann et al. (2010, 2013). Knowledge from these and other publications was collected by Fernández (2014b) in a review on the applicability of those methods to schedule irrigation in commercial orchards. He concluded that the ZIM system was one of the most promising systems for commercial olive orchards. The system is easier to install and use than those of sap flow and trunk diameter variation, and as robust as those two when working under field conditions for the long irrigation seasons common in most olive growing areas. On the outputs, Fernández (2014b) showed that both sap flow and trunk diameter related measurements require high training both to process the collected data and to understand their physiological meaning. For the leaf turgor related measurements, he stated that, although we are still far from fully understanding the physiological meaning of the ZIM probe readings, there was a potential for scheduling irrigation based just on the visual analysis of the P_p daily curves. This is crucial for the acceptance of any method to schedule irrigation by farmers and orchardists without specific training, as previously stated by Naor (2006 and Fernández and Cuevas (2010), among others.

Our results suggest that we cannot expect a robust correlation between the tree water status and P_p values for the whole irrigation season (Fig. 4). This is not surprising, since aging induces structural and mechanical changes in the olive leaf that could easily affect the outputs of the ZIM probes. Thus, the water stress history of the leaf can affect the palisade parenchyma (Chartzoulakis et al., 1999; Bacelar et al., 2004), as well as the density and thickness of the leaf (Centritto, 2002). The seasonal course of the Ψ_{stem} *vs*. P_p relationship can also be affected by changes in the elastic modulus (ε) of the leaf cells. It has been observed that, in olive, ε tends to increase with leaf age (Bongi and Palliotti, 1994) and drought (Dichio et al., 2003). All these changes, together with others on leaf response to environmental stimuli (Marchi et al., 2008) can affect the Ψ_{stem} *vs*. P_p relationship along the season. The fact that, at least for olive, the Ψ_{stem} *vs*. P_p relationship changes with time must be taken into account when P_p values are used to derive water stress indices requiring normalization, as for the case described by Bramley et al. (2013). Figure 4, in fact, suggests that establishing an effective normalization procedure of the P_p records is not straightforward.

Our irrigation approach (Section 2.1), however, does not rely on absolute P_p values, but on changes between States, which it does not require normalization. Our hypothesis was that findings by Fernández et al. (2011) and Ehrenberger et al. (2012) reported for young trees, also holds for mature, fully productive trees. This is, in fact, supported by Fig. 5, which shows that the relation between the State of the P_p curve and the ranges of tree water status defined by Fernández et al. (2011) and Ehrenberger et al. (2012) holds reasonably well for olive trees of different age growing under a wide range of environmental variables. This supports the potential of the change in the State of the daily P_p curve as a user-friendly, visual indicator for irrigation scheduling. Such potential was confirmed in 2014, when we used our irrigation approach to schedule irrigation of treatment $45RDI_{TP}$. In period 2 the IA values derived from our approach were lower than those calculated from the crop coefficient approach, i.e. those of the $45RDI_{CC}$ treatment (Figs. 7A,B). For that period, the reduced irrigation in $45RDI_{TP}$ as compared to that in $45RDI_{CC}$ did not lead to differences in plant water status (Fig. 3), despite of the greater water savings achieved with our irrigation approach. In period 3 differences between our approach and that of the crop coefficient were less evident (Figs.

7C,D). Results from a single year, however, might not be enough to reliably state differences between both approaches.

With our irrigation approach we managed to keep similar stress levels in the $45RDI_{TP}$ trees than in the FI trees, during the sensitive periods 2 and 3 (Fig. 3). As compared to the $45RDI_{CC}$ treatment, our irrigation approach showed similar results in terms of tree water stress level, and greater water savings. In addition to that, yield and irrigation water productivity values were similar in $45RDI_{TP}$ than in $45RDI_{CC}$. Although more years are required to evaluate the impact of these two approaches on crop performance and water productivity, these results suggest that our irrigation scheduling approach leads to similar values of both variables, if not better, than the crop coefficient approach .

The reported advantages of $45RDI_{TP}$ as compared to $45RDI_{CC}$ might not be enough to recommend adopting our irrigation approach in all cases. If both reliable K_c values and a nearby weather station are available, the crop coefficient approach can be a good option to apply the 45RDI strategy (Fig. 1) in hedgerow olive orchards with high plant densities. Those conditions, however, are not accomplished in most olive orchards. Then, our irrigation scheduling approach based on the ZIM system can be used with confidence to schedule irrigation. Still, there are empirical aspects in our approach that must be further addressed. These refer to increasing or decreasing IA by 15% in periods 2 and 3, and to using IA = 120% IN on the first three days of those periods. Such values are purely empirical and require further attention. In addition, our irrigation scheduling approach based on the ZIM system does not provide information to estimate IA in between periods 1 and 2, 2 and 3, and after period 3. On those days IA must be based on whatever knowledge the farmer has on the orchard water needs, which may led to imprecise results. Still, the advantage of our irrigation scheduling approach, as compared to the crop coefficient approach, can be especially remarkable in large orchards where soil, plant and atmospheric conditions are highly variable. In those cases the crop coefficient approach can led to large errors, at least for certain parts of the orchard where the used K_c values fit worst. In those orchards is where the use of ZIM sensors, combined with remote infrared images for selecting the trees to instrument (Zarco-Tejada et al., 2009; Gonzalez-Dugo et al., 2013), could show a better performance.

5. Conclusions

Our irrigation scheduling approach, based on the use of the ZIM system, allowed for an effective application of regulated deficit irrigation in a hedgerow olive orchard with high plant density. Our irrigation scheduling approach can be used by farmers without specific training, since it is based on the State shown by the outputs from the ZIM sensors. The State can be easily identified, just by visualising the daily curves derived from the raw outputs collected by ZIM sensors, without any further data processing. Our results proved a robust enough relation between States 1 to 3 shown by the P_p curves and water stress levels in olive trees. This relation, previously established for young trees by our group and by the group that developed the ZIM system, also holds for mature, fully productive olive trees growing under a wide range of environmental conditions. Our irrigation scheduling approach showed a performance as good as that of the crop coefficient approach, and can led to a more precise irrigation scheduling in large, highly variable orchards. There is still room, however, for further elucidating aspects of our approach that, in its current state, are purely empirical.

6. Acknowledgements

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Fig. 1. Regulated deficit irrigation strategy applied in the orchard for the 45RDI treatments. In the three periods of high crop sensitivity to water stress (periods 1 to 3), irrigation is applied daily. For the rest of the year just one or two irrigation events per week (i.e./w.) are applied, replacing 10% or 20% of the total irrigation needs (IN) in the period. AW is the available water in the soil. Both the double sigmoidal curve for growth and the sigmoidal curve for oil accumulation are observed in years with very hot and dry summers. In years with less demanding conditions, both variables show a linear increase along the summer. ET_c = crop evapotranspiration; P_e = effective precipitation, assumed to be 75% of the precipitation recorded by a weather station in the orchard; WAB = weeks after bloom. After Fernández et al. (2013).

Fig. 2. Seasonal courses of both the irrigation amounts (IA) supplied to each treatment and the precipitation (*P*) collected in the orchard (A,B), and the values of relative extractable water (REW) derived from the soil water contents (avg – SE) measured in the plots of each treatment (C,D). Measurements were made on the irrigation seasons of 2013 and 2014. Different letters indicate significant differences between treatments, at $p < 0.05$. Letters are not shown when no differences were found. DOY = day of year.

Fig. 3. Seasonal courses of predawn water potential (Ψ_{pd}, avg ± SE) and midday stem water potential (Ψ_{stem}, avg ± SE) measured in 2013 (A, B) and 2014 (C, D) in FI, $45RDI_{cc}$ and $45RDI_{TP}$ trees. Different letters indicate significant differences between treatments at $p < 0.05$. Letters are not shown when no differences were found. DOY = Day of year.

Fig. 4. Daily curves of the ZIM probe outputs (P_p) installed in a representative tree of the $45RDI_{CC}$ (A) and FI (B) treatments applied in 2013. The shown curves correspond to days prior (May) and after (September) the most demanding, in terms of water stress, mid-summer period. Also shown are predawn (Ψ_{pd}, avg ± SE, triangles) and midday stem water potential (Ψ_{stem}, avg ± SE, circles) values measured with a Scholander-type pressure chamber in trees next to the trees instrumented with ZIM probes, also in May and September. Both for the curves and symbols, the grey and black colours mean measurements in May and the September, respectively.

Fig. 5. Midday stem water potential (Ψ_{stem}) values measured in representative trees of all the irrigation treatments at the Sanabria orchard during the irrigation seasons of 2010 to 2014. Each data point corresponds to a single measurement with a Scholander-type pressure chamber. Dashed lines represent the midday stem water potential values values identified by Fernández et al. (2011a)

and Ehrenberger et al. (2012) as typical of State 1 (Ψ_{stem} > -1.2 MPa) (A), State 2 (-1.2 MPa > Ψ_{stem} > -1.7 MPa) (B) and State 3 (Ψ_{stem} < -1.7 MPa) (C). The State is given by the shape of the daily leaf patch clamp pressure curve, as described by Ehrenberger et al. (2012). DOY = Day of year.

Fig. 6. Seasonal courses of midday stem water potential (Ψ_{stem}, avg. ± SE) measured in FI, 45RDI$_{CC}$ and 45RDI$_{TP}$ trees of the Sanabria orchard during the whole irrigation season of 2014. P_p curves were collected by three ZIM probes per treatment and shown here through State 1 (low water stress), State 2 (moderate stress) and State 3 (severe stress) by horizontal colour bars. Periods 2 and 3 shown in Fig. 1, as observed in this year 2014, are represented. DOY = Day of year.

Fig. 7. Time courses of the P_p values recorded on a 45RDI$_{TP}$ representative tree in period 2 (A) and period 3 (C) of the 2014 irrigation season (see Fig. 1 to identify the periods). Also shown are the irrigation amounts (IA) supplied to each treatment in each period (B,D), expressed as a fraction of the calculated irrigation needs (IN) for the period. IA was increased (arrows up) or decreased (arrows down) according to changes in the State of the daily P_p curves (see the irrigation approach described in Section 2.1). DOY = Day of year.

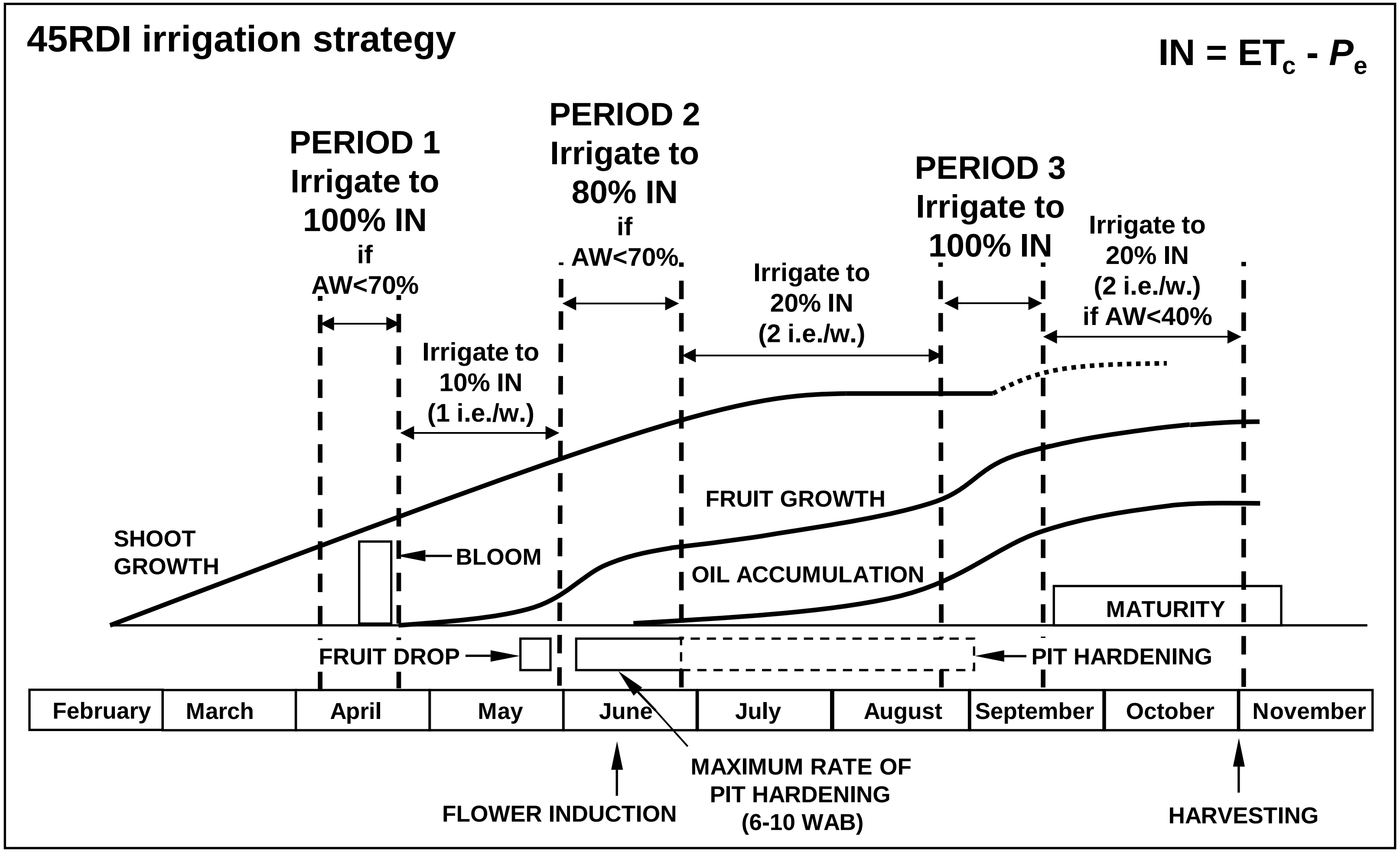
Table 1. Water supplies (IA = irrigation amounts; *P* = precipitation) and potential evapotranspiration (ET_o) in the experimental orchard for the two irrigation seasons. All values are in millimeters. Values of IA are also expressed as percentages of irrigation needs (% IN). DOY = day of year.

	2013		2014	
	Whole year	Irrigation period (DOY 133–301)	Whole year	Irrigation period (DOY 116–324)
ET_o	1464.3	1000.3	1437.6	1110.1
P	476.4	112.5	549.4	317.6
IA in FI		367.6 (80.0% IN)		462.9 (87.1% IN)
IA in $45RDI_{CC}$		197.9 (43.1% IN)		238.2 (44.8% IN)
IA in $45RDI_{TP}$				235.9 (44.4% IN)

Table 2. Fruit yield (n = 4) and water productivity values for each treatment and experimental year. Different letters indicate significant differences between treatments at $p<0.05$.

Year	Treatment	Fruit yield (kg ha^{-1})	Irrigation water productivity (kg ha^{-1} mm^{-1})
2013	FI	22559.8 ± 1453.1 a	61.4* ± 3.9 a
	45RDI$_{CC}$	14952.1 ± 873.0 b	75.6* ± 4.4 b
2014	FI	19283.0 ± 2708.5 a	41.6 ± 5.9 a
	45RDI$_{CC}$	13443.0 ± 2847.9 a	53.4 ± 12.0 a
	45RDI$_{TP}$	17025.6 ± 2077.0 a	72.2 ± 8.8 a

Data with * were affected by reduced water supply at the beginning of the irrigation season (see Section 3 for details).



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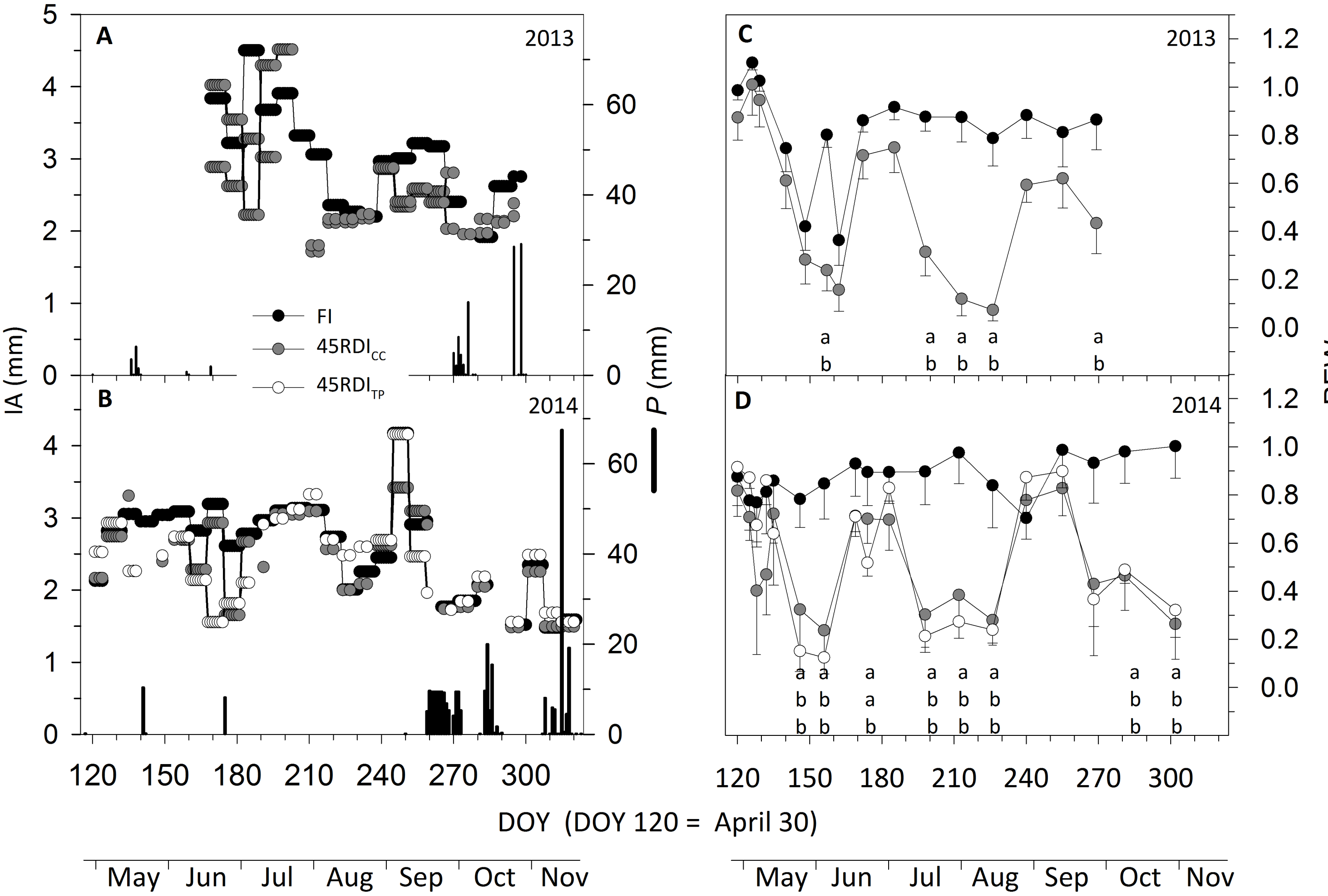

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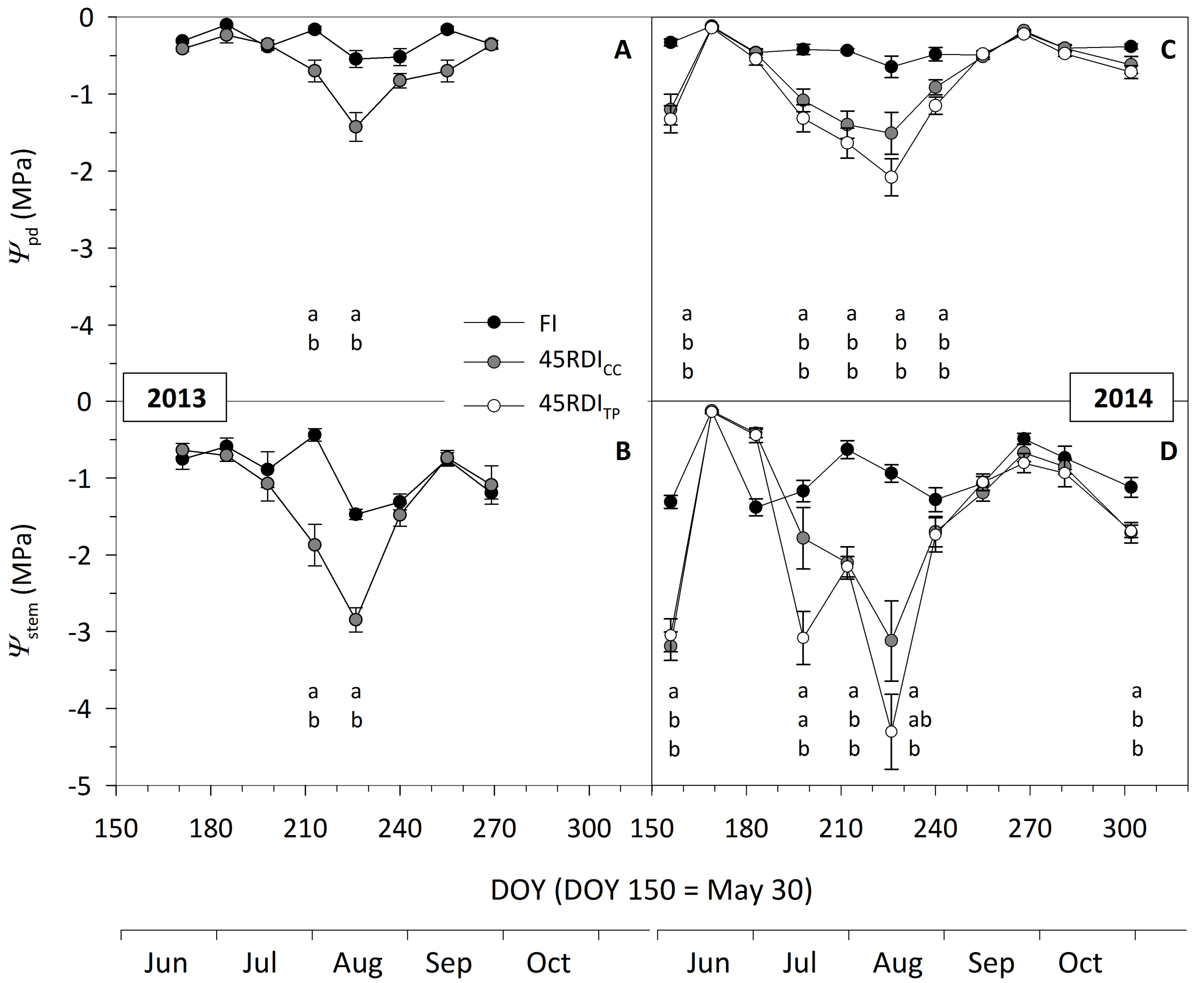

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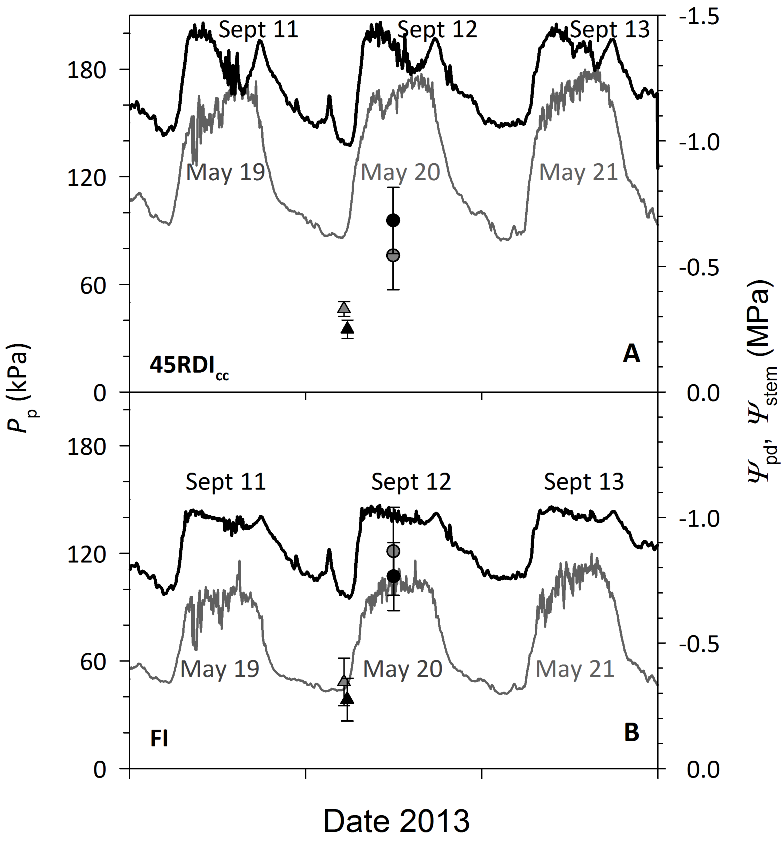

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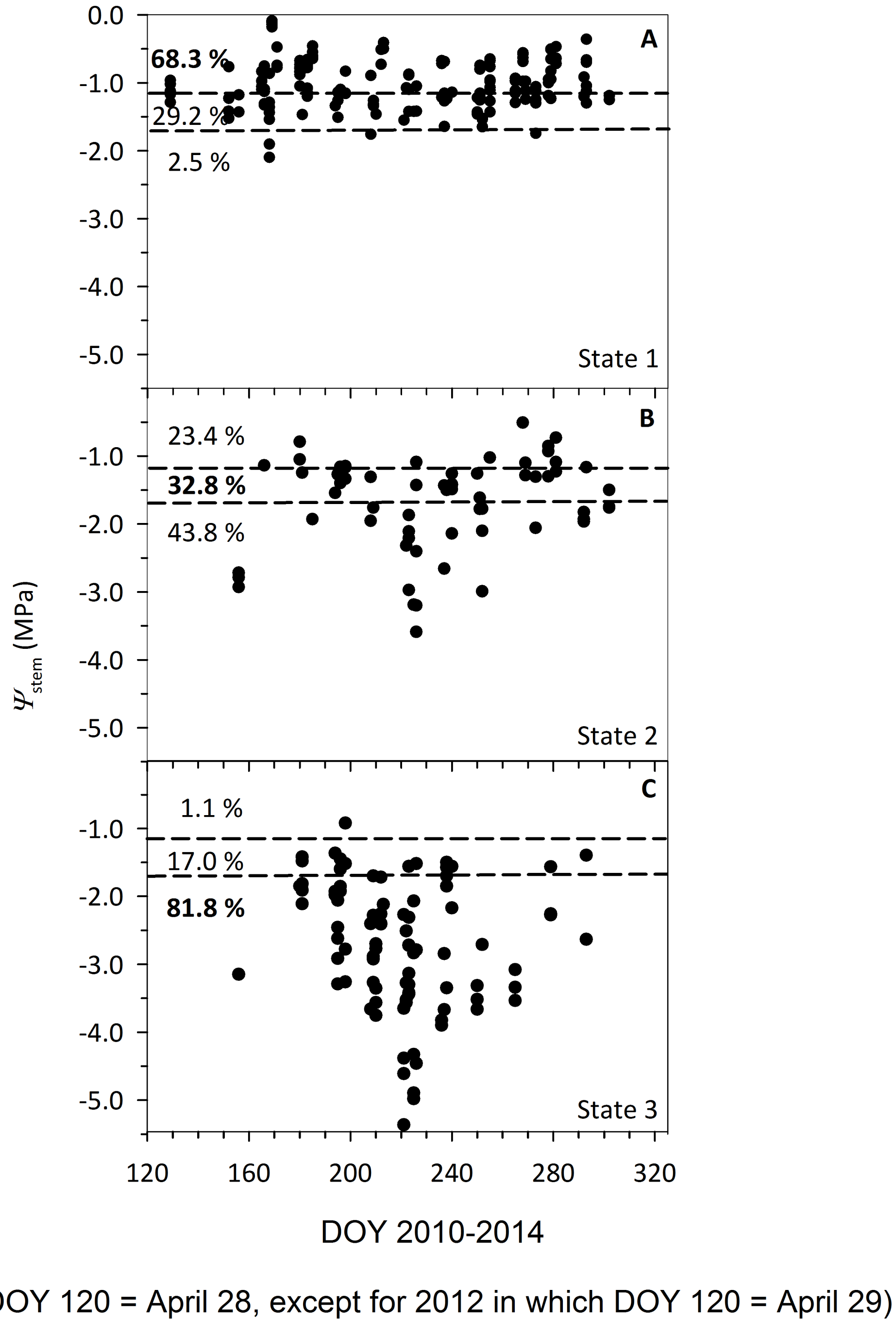

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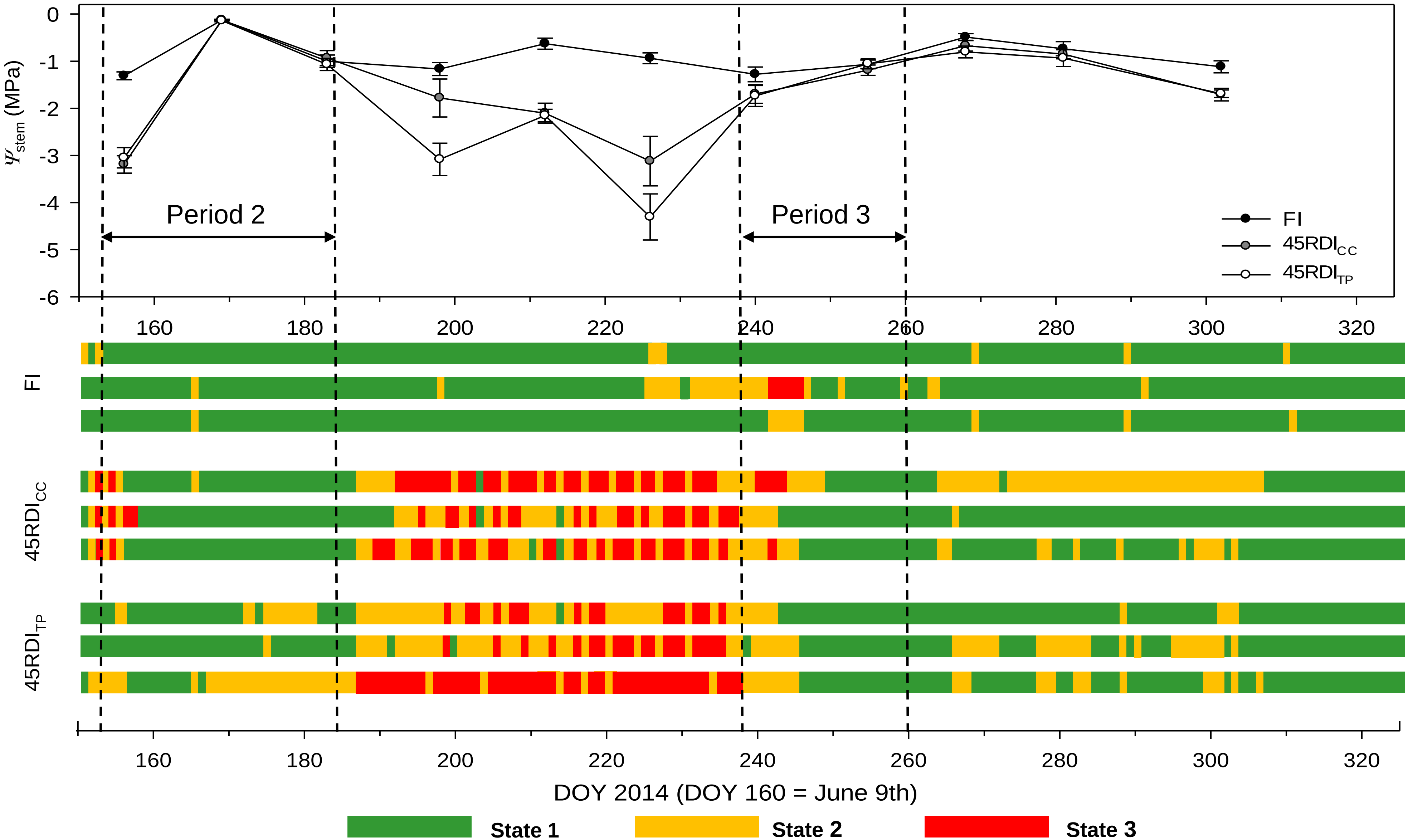

Fig. 6. Seasonal courses of midday stem water potential (Ψ_{stem}, avg. ± SE) measured in FI, $45RDI_{CC}$ and $45RDI_{TP}$ trees of the Sanabria orchard during the whole irrigation season of 2014. P_p curves were collected by three ZIM probes per treatment and shown here through State 1 (low water stress), State 2 (moderate stress) and State 3 (severe stress) by horizontal colour bars. Periods 2 and 3 shown in Fig. 1, as observed in this year 2014, are represented. DOY = Day of year.

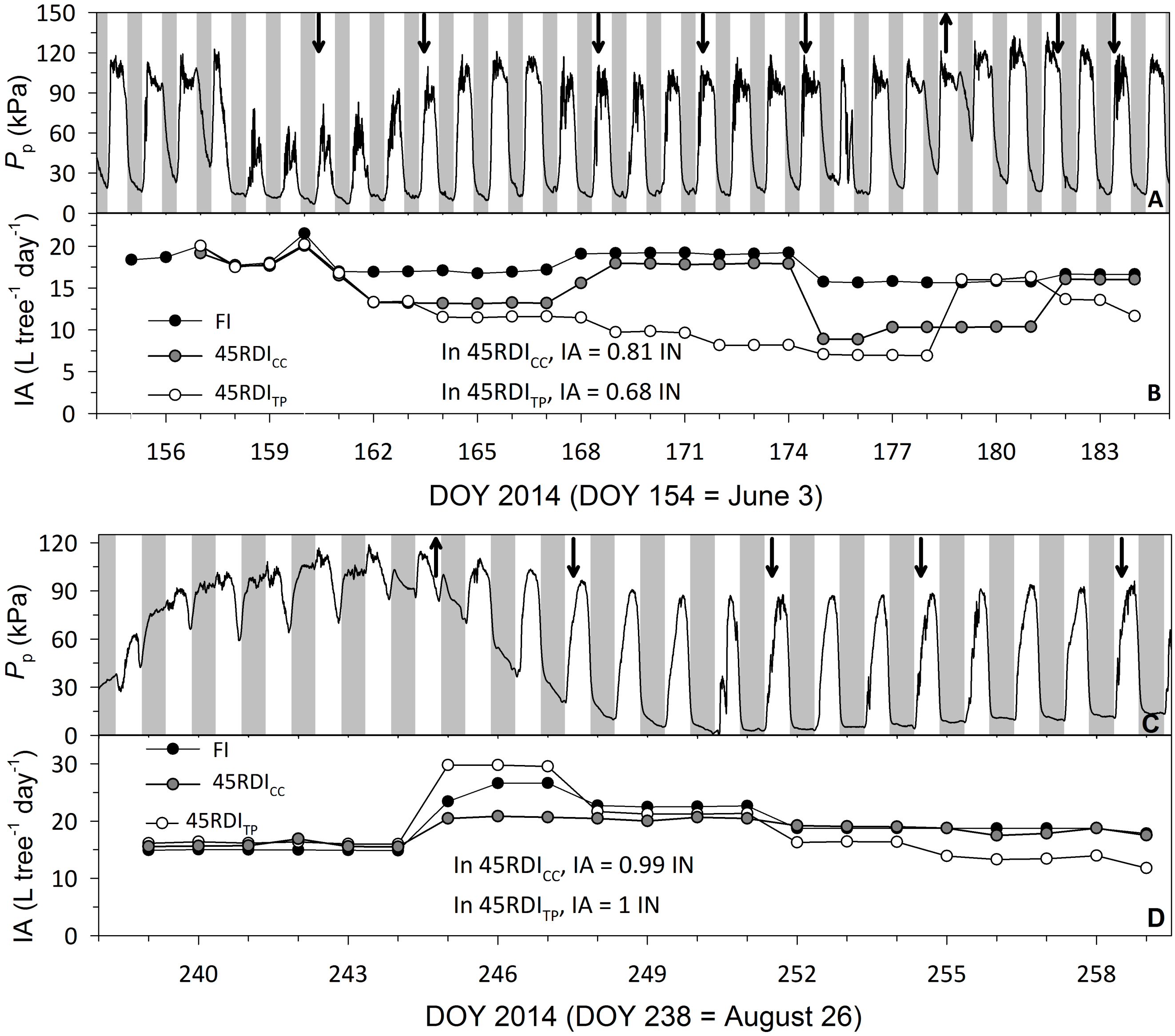

Fig. 7. Time courses of the P_p values recorded on a 45RDI$_{TP}$ representative tree in period 2 (A) and period 3 (C) of the 2014 irrigation season (see Fig. 1 to identify the periods). Also shown are the irrigation amounts (IA) supplied to each treatment in each period (B,D), expressed as a fraction of the calculated irrigation needs (IN) for the period. IA was increased (arrows up) or decreased (arrows down) according to changes in the State of the daily P_p curves (see the irrigation approach described in Section 2.1). DOY = Day of year.